Delayed deglaciation or extreme Arctic conditions 21-16 cal. kyr at southeastern Laurentide Ice Sheet margin?

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[1] The conventionally accepted ages of the Last Glacial Maximum (LGM) retreat of the southeastern Laurentide Ice Sheet (LIS) are 26–21 cal. kyr (derived from bulk-sediment radiocarbon ages) and 28–23 cal. kyr (varve estimates). Utilizing accelerator mass spectrometry (AMS) ^{14}C dating of earliest macrofossils in 13 lake/bog inorganic clays, we find that vegetation first appeared on the landscape at 16–15 cal. kyr, suggesting ice had not retreated until that time. The gap between previous age estimates and ours is significant and has large implications for our understanding of ocean-atmosphere linkages. Older ages imply extreme Arctic conditions for 9–5 cal kyr; a landscape with no ice, yet no deposition in lakes. Our new AMS chronology of LIS retreat is consistent with marine evidence of deglaciation from the N. Atlantic, showing significant freshwater input and sea level rise only after 19 cal kyr with a cold meltwater lid, perhaps delaying ice melt. **Citation:** Peteet, D. M., M. Beh, C. Orr, D. Kurdyla, J. Nichols, and T. Guilderson (2012), Delayed deglaciation or extreme Arctic conditions 21-16 cal. kyr at southeastern Laurentide Ice Sheet margin?, *Geophys. Res. Lett.*, *39*, L11706, doi:10.1029/2012GL051884.

1. Introduction

[2] The history of the retreat of the southeastern margin LIS is particularly relevant today as Greenland warms and meltwater enters the N. Atlantic. Enormous amounts of fresh water were released into the N. Atlantic following LIS ice melt [*Keigwin et al.*, 1991], and an influx of freshwater into the North Atlantic Deep Water (NADW) formation zone remains a viable hypothesis for triggering abrupt climate change [*Broecker et al.*, 1985]. However, we find four lines of evidence which conflict with the conventionally accepted age of 26–21 kyr for southeastern LIS deglaciation [*Dyke et al.*, 2003], pointing to a much later deglaciation. These include the AMS ^{14}C-dated lake inception ages presented here, evidence of minimal meltwater input before 19 cal. kyr [*Keigwin et al.*, 1991], minimal sea level rise until 19 cal. kyr [*Yokoyama et al.*, 2000; *Peltier and Fairbanks*, 2006], and N. Atlantic sea surface temperature (SST) decline at 17–16 cal. kyr [*Bard et al.*, 2000].

[3] The timing of the LIS retreat has heretofore presented an enigma, as disparate data sources have offered conflicting chronologies of retreat from the terminal NY – NJ – PA position. We address this conundrum with a new chronology, which includes 7 new sites, based on AMS ^{14}C dates of the first identified individual terrestrial macrofossils at the base of sediment cores. Dating only terrestrial macrofossils ensures that no contamination from refractory carbon or carbonate rocks will influence our results, thus avoiding the issues that arise from dating bulk sediment. Our results demonstrate that 13 lake and bog sites across the southeastern LIS margin did not accumulate basal clays and silts until 16–14.5 cal. kyr. This estimate implies that either deglaciation occurred much later than originally estimated, or ice-free Arctic conditions prevailed in eastern North America without deposition in sedimentary basins for at least 5 millennia. In light of our new data, we provide a framework for reinterpreting the considerably older (28–23 cal. kyr) existing chronologies, based on ^{10}Be exposure ages and varve sequences from large valleys throughout the Northeast U.S. Further, we review evidence for the timing of deglaciation from circum-North Atlantic sites and discuss the implications of the dating disagreements.

2. Methods

[4] We targeted a characterization of the deglacial environment from 13 lakes/bogs in the southeastern sector of the LIS margin likely to have late-glacial macrofossil records suitable for AMS ^{14}C dating. These included re-visiting several sites that were previously used for paleoclimatic analysis - Linsley Pond, CT and Tannersville, PA as well as sites adjacent to key sites such as Allamuchy Pond adjacent to Francis Lake, NJ and Linsley Pond near Rogers Lake, CT as well as 7 new sites throughout the region (Figure 1 and Table S1 in the auxiliary material).[1] Our aim was to identify both bedrock sites (e.g., Alpine, NJ) as well as those in till (e.g., Allamuchy Pond, NJ; High Rock, NY) adjacent to the terminal glacial moraine (Figure 1) and to identify and describe the earliest sedimentary environments concurrent with ice retreat, using terrestrial plant fossils preserved in the initial inorganic sediments. Bulk sample radiocarbon ages of lake bottom sediments are now commonly known to have large errors of 1–2 kyr and as large as 10 kyr [*Ridge*, 2004; *Grimm et al.*, 2009], and we thus focused on dating terrestrial plant macrofossils in clays. A modified Livingstone piston corer with fixed extension rods was used to "saw" through mineral sediments in order to reach basal till or bedrock. These basal core sections were sub-sampled contiguously at 2-cm intervals and screened and picked for macrofossil analysis and loss-on-ignition (LOI). Identified samples for AMS ^{14}C dating were chemically pretreated (acid-base-acid),

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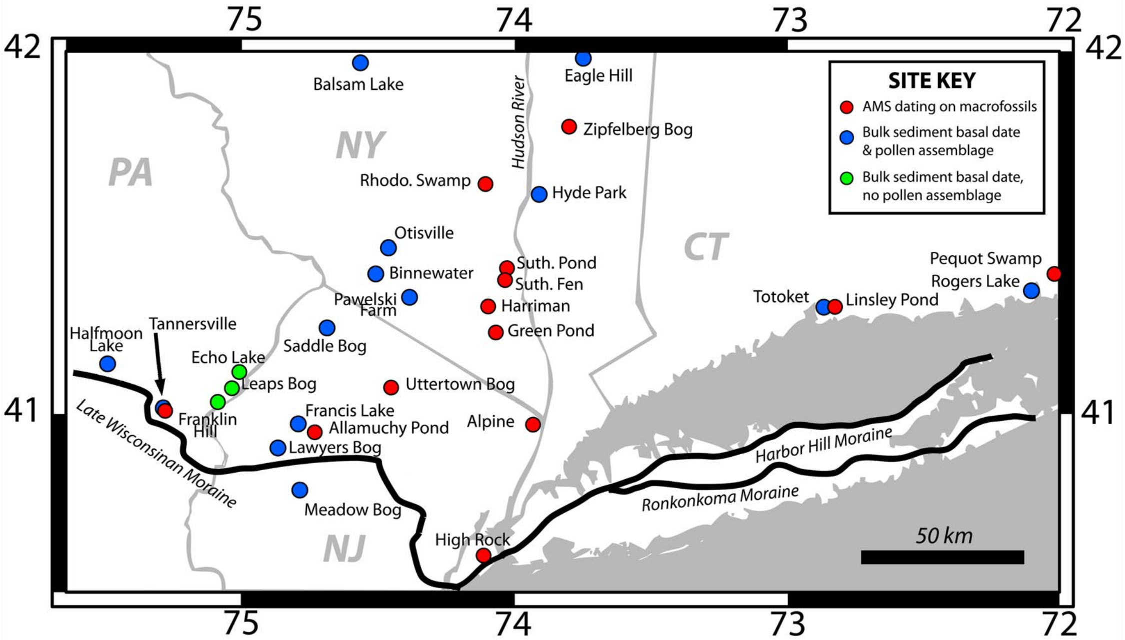

Figure 1. Map of southern Laurentide margin lake sites where sediment cores have been collected and radiocarbon dating utilized to define the timing of deglaciation.

combusted via individual sealed tubes, and the resulting CO_2 reduced to graphite in the presence of an iron catalyst and a stoichiometric excess of hydrogen. The Calib 6 program and IntCal09 were used to convert ^{14}C ages to calendar ages [*Reimer et al.*, 2009].

3. Results and Discussion

3.1. AMS ^{14}C Ages on Terrestrial Macrofossils in Clays

[5] We assess the timing of the deglaciation in the Hudson Valley, Connecticut, and New Jersey using 13 AMS ^{14}C dated terrestrial macrofossils (Figures 1 and 2 and Table S1). Table S1 also includes dates upcore in the gyttja at some sites. Macrofossils used in these analyses were recovered from the blue-grey or reddish clays and silts that characterize basal sediments above bedrock or till. The loss-on-ignition (LOI) measured for these sediments reveals extremely low organic matter content (0.5–8%) in these late-glacial sediments, comparable to modern lakes in the prostrate shrub tundra of the high Canadian Arctic [*Peros and Gayewski*, 2009]. Pollen influx in the inorganic clays at Sutherland Pond [*Maenza-Gmelch*, 1997] indicates extremely low pollen abundance (<100 grains/cm^2/yr), further evidence of a very sparsely vegetated landscape, again comparable to the modern Canadian Arctic [*Peros and Gayewski*, 2009]. Our suite of new AMS-dates, in contrast to 14 older bulk dates (Figure 2), demonstrates a close cluster of deglaciation ages between 12.2 and 12.7 ^{14}C kyr (14.0 –15.6 cal. kyr). Two sites, which are slightly older, date to 13.1–13.2 ^{14}C kyr (15.9–16.7 cal. kyr), but the uncertainty in age ranges, plant migration routes, and growth on glaciers may minimize this difference.

[6] Dates in the new suite of sites are at least 7–10 cal. kyr younger than the previously estimated ages of 20–22 ^{14}C kyr (23–26 cal. kyr, Figure 3). As such they represent consistent evidence for ice and/or extreme Arctic conditions remaining at the southern Laurentide margin much longer than the traditional bulk chronologies and maps depict [*Dyke et al.*, 2003]. The migration rate of plants depends greatly on proximity to seed source, which was available minimally 150 km south of the ice sheet at Crider's Pond, Pennsylvania [*Watts*, 1979]. Colonization studies of tundra vegetation such as mountain avens (*Dryas*) and willow (*Salix*) on unconsolidated glacial deposits in Glacier Bay, AK indicates a mere 12–15 yr lag, with about 100 years for spruce (*Picea*) [*Fastie*, 1995]. Thus we infer that the AMS-dated tundra and spruce macrofossils in basal clays represent the initial colonization of the landscape at 15.5–16 cal. kyr coincident with widespread climatic amelioration and ice-free conditions. Absence of sand layers in the basins atop basal till argues against

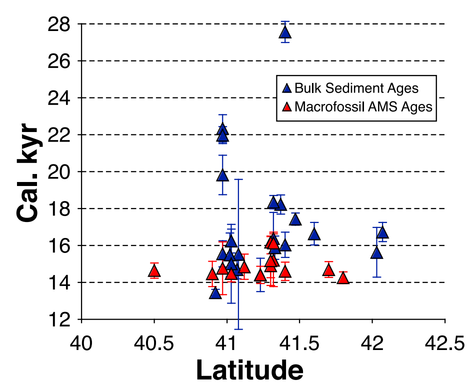

Figure 2. Suite of calendar ages (kyr) calibrated using CALIB6 [*Reimer et al.*, 2009] from AMS ^{14}C dates on plant macrofossils at 13 sites, including 7 new lakes. Dates cluster at 14.5–15.6 cal kyr, with 2 sites 16.1 and 16.7 cal kyr. Bulk radiocarbon ages (blue), are generally significantly older. 2σ error bars are given.

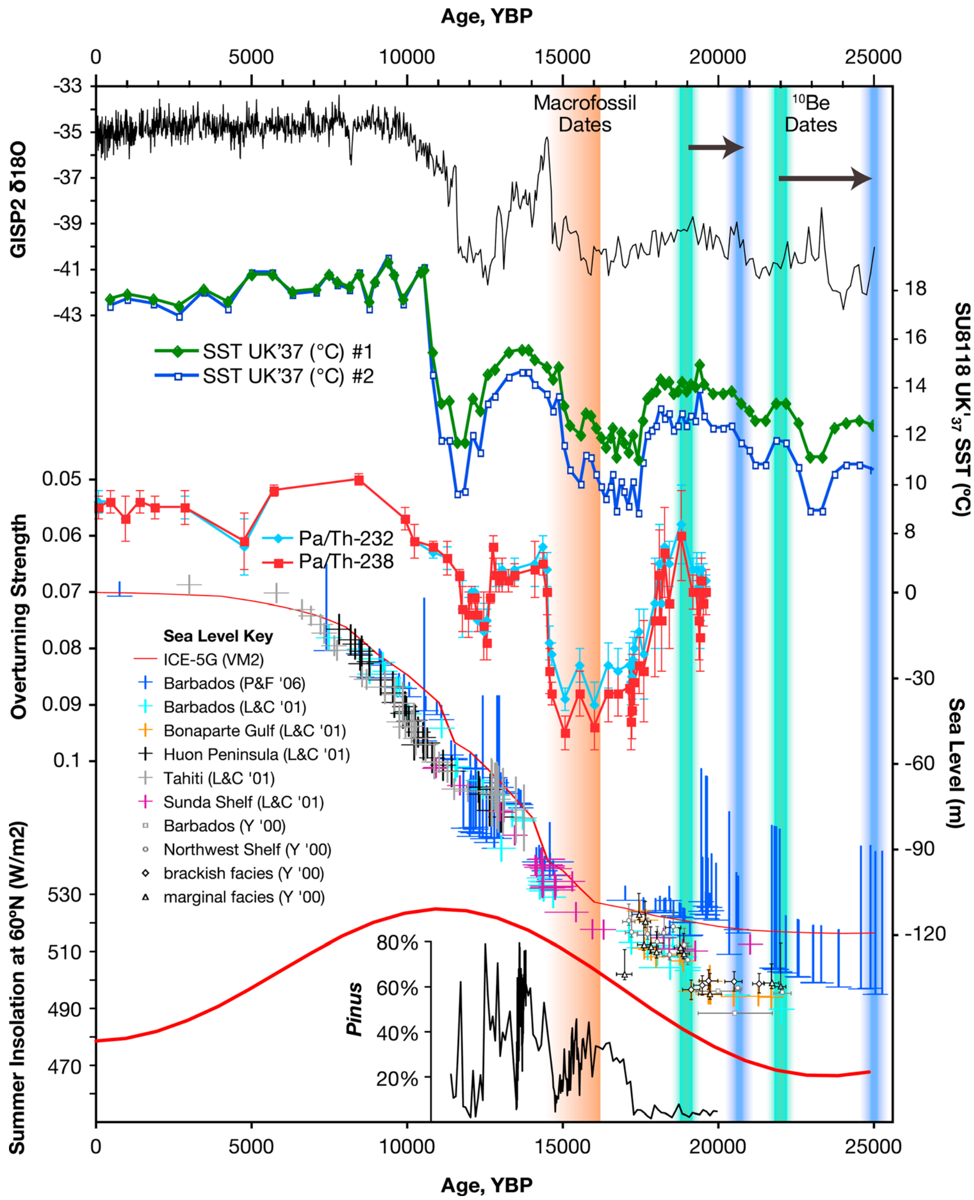

Figure 3. Comparison of new set of AMS ^{14}C ages on terrestrial plant macrofossils clustered between 16 and 14.5 cal. kyr (Figure 2) (pink shading) with ^{10}Be ages from boulders along the moraine first calibrated as 19 cal. kyr in Conn. and 22 cal. kyr in NJ (green shading) [*Balco et al.*, 2006]: then re-calibrated (arrows) to 21 cal. kyr in Conn. and 25 cal. kyr in NJ (blue shading) [*Balco et al.*, 2009]; and GISP2 isotope record [*Stuiver and Grootes*, 2000]; N. Atlantic records for SST from alkenone rations from core SU-8118 off Portugal [*Bard et al.*, 2000] and ^{231}Pa/^{230}Th profile from core GGC5 from the Bermuda Rise [*McManus et al.*, 2004]; as well as sea level records from corals [*Yokoyama et al.*, 2000; *Lambeck and Chappell*, 2001; *Peltier and Fairbanks*, 2006]; the N. hemisphere summer insolation curve at 60°N [*Berger et al.*, 1978]; and *Pinus* pollen as a warmth indicator in the Tampa Bay pollen record [*Willard et al.*, 2007].

widespread landscape instability and a shifting depositional environment.

3.2. Age of the Southeastern Laurentide Deglaciation: A Longstanding Radiocarbon Controversy

[7] The origin of the debate over the age of the southeastern LIS retreat began with a chronology based on radiocarbon ages of bulk sediment, which is problematic because bulk sediment contains carbon of uncertain provenance, such as carbonate rocks as well as fine-grained clastic material from coal and shale as well as reworked refractory organic matter [*Grimm et al.*, 2009]. *Cotter et al.* [1986] retrieved two bulk sediment dates of 18.4 and 18.6 ^{14}C kyr (23.3 cal. kyr) from Francis Lake, NJ (Figure 1 and Table S1) and argued for an early regional deglaciation despite considerable controversy over the validity of these ages because of hard water contamination [*Karrow et al.*, 1986]. To the north, in the Wallkill Valley [*Connally and Sirkin*, 1986], similarly estimated deglaciation prior to 18.5 ^{14}C kyr (21–23 cal. kyr). These estimates were based on extrapolated sedimentation rates below intervals dated with ^{14}C ages of bulk sediment. *Stone et al.* [2002] infer the Rahway till deposition in northern New Jersey to be between 26 and 17.8 ^{14}C kyr (29–20 cal. kyr), based upon few bulk dates

such as Francis Lake, NJ [*Cotter et al.*, 1986]. Similarly, an age of about 21–19.5 ^{14}C kyr (23–21 cal. kyr [*Stone and Borns*, 1986]) is accepted for the western segment of the Harbor Hill, Long Island moraine based upon bulk dates. Thus, basal bulk ^{14}C lake chronologies and extrapolation established the paradigm of an early deglaciation, the backdrop from which we recognized an imperative need to acquire basal lake/bog sediments from macrofossils to improve the chronology.

3.3. Cosmogenic Nuclide Exposure Dating of the Southeastern Laurentide

[8] Cosmogenic-nuclide exposure dating of the last glacial maximum seems consistent in southern New England [*Balco and Schaefer*, 2006], but exposure dating requires the derivation of a local nuclide production rate. *Balco and Schaefer* [2006] first derived a production rate for ^{10}Be using radiocarbon dates of bulk sediment, varves, or a single outlier AMS date in sands. Their production rate agreed with that of *Clark et al.* [1995] who also used radiocarbon dates of bulk sediment. *Balco and Schaefer* [2006] thus derived an age of deglaciation of 22.1 cal. kyr. However, more recently *Balco et al.* [2009] utilized varve chronologies from New England to re-calculate the deglacial age for the NJ terminal moraine near 25 cal. kyr, and the CT moraines at 21 cal kyr (see arrows in Figure 3).

[9] *Balco and Schaefer* [2006] briefly note that the bulk radiocarbon ages for eastern Connecticut [*Stone and Borns*, 1986] are rarely greater than 12.7 ^{14}C kyr (15 cal. kyr). These authors rejected the relatively young ages, attributing them to the late regional onset of lake organic sedimentation or to the expansion of wetlands due to beavers [*Balco and Schaefer*, 2006]. However, we demonstrate that in the lake clay layers the onset of tundra/boreal macrofossils is sometimes at least a millennium prior to organic sedimentation, and thus argue that the dates rejected by *Balco and Schaefer* [2006] reflect widespread initial ice retreat coupled with landscape stabilization as tundra colonized the region. The sole anomalous AMS date on tundra macrofossils of 15.2 ^{14}C kyr (18–19 cal kyr) from Pequot Swamp, CT (Figure 1) [*McWeeney*, 1994], is found in massive sands 3 meters below the initiation of lacustrine sediments. Indicative of sedimentologically unstable conditions, it invokes ice-walled lakes such as existed in the Midwest with ice still present [*Curry et al.*, 2010] on the landscape throughout the region. Debris on the surface of glaciers often support plants [*Fickert et al.*, 2007] and debris could have supported this single older dated tundra macrofossil in this compilation. The question arises as to how an early deglaciation implied by cosmogenic dates can be reconciled with the widespread and consistent (Figures 1–3) record of lake initiation 6–9 millennia later. While basal lake dates are minimal ages for deglaciation, it is unreasonable to invoke total lack of deposition for multiple millennia. Rather than invoking a frigid environment lacking lake formation for at least 6 millennia, we propose a re-calculation of ^{10}Be production rates replacing radiocarbon dates of bulk sediment with AMS dates of macrofossils of known origin to improve our understanding of ice retreat chronology.

3.4. Varve Chronologies in the Northeastern US

[10] *Ridge*'s [2004] varve chronology indicates a deglaciation scenario at 20–25 ^{14}C kyr (23.7–28 cal. kyr). However, this early part of the floating varve chronology is anchored solely by inferred correlations to Greenland ice core oxygen isotopes [*Ridge*, 2004]. In contrast, the latter part of the deglaciation 15–11.5 ^{14}C kyr (18 – 13.4 cal. kyr) is tied to AMS ^{14}C dates on macrofossils within varves from New England glacial lakes in the Connecticut, Merrimack, Passumpsic, and Winooski Valleys. However, no dates are present for the varve sequences in the southeastern sector (i.e., Newburgh, Haverstraw, or New Jersey sequences at the southern margin of the ice sheet). Ridge thus adds these southern varves to the existing dated chronology and derives a deglaciation age of 20–25 ^{14}C kyr (23.7–28 cal. kyr), which is 3–6 cal. kyr older than the legacy of older bulk ages from the region [*Connally and Sirkin*, 1986; *Stone et al.*, 2002], and is 8–12 cal. kyr older than our AMS chronology. One possible explanation for this conflict is that large valley glacial lakes received sediment input from adjacent uplands with summer meltwater (solifluction), while the landscape around them was still predominantly ice-covered. The resulting number of varves would imply an early deglaciation, while actual ice-free conditions occurred many millennia later. Modern analogs for classic varved sediments in lakes, which are ice-covered eleven months of the year, occur in the high Arctic (e.g., Ellesmere Island). These lakes are open only for a few weeks a year, and summer snowmelt produces coarser silt layers with winter fine settling resulting in a clay cap [*Francus et al.*, 2008]. Thus, varves may accumulate while melting ice is still present, producing a seemingly longer chronology, which is ultimately misleading in terms of time elapsed since final regional deglaciation.

3.5. Comparison With Terrestrial Sites in Circum-North Atlantic Region: Southeastern US and Europe

[11] The AMS-dated pollen and macrofossil record at Brown's Pond, VA, 300 km south of the ice margin, shows that as the record begins at 17.3 ^{14}C kyr (20–21 cal. kyr), a moist climate is indicated by the presence of fir trees in addition to spruce [*Kneller and Peteet*, 1993]. Beginning about 14 ^{14}C kyr (16.5–18 cal. kyr) slight warming took place followed by dramatic warming at 12.5 ^{14}C kyr (14–15 cal. kyr) just as in sites north of the ice sheet. Initial warming at 17 cal. kyr is recorded as well as in a very high-resolution late-glacial *Pinus (*pine*)* record from Tampa Bay (Figure 3) [*Willard et al.*, 2007]. It therefore appears possible that a 20–17 cal. kyr warming initiated southeastern Laurentide ice melt downward, but it took about two thousand years for the terminal moraine landscape to be ice-free and lakes to record early colonization.

[12] In Europe, the lake chronologies similarly point to a slight warming as early as 20 cal. kyr in southern France and Spain but widespread and sustained warming only after 15 ^{14}C kyr (17–18 cal. kyr) (see synthesis in *Walker* [1995]). The pattern of warming at 17 cal. kyr in the Orca and Cariaco Basins in the Gulf of Mexico [*Williams et al.*, 2010] matches the timing of widespread warming in terrestrial records [*Willard et al.*, 2007, and references therein], but these records do not go back as far as 23 cal. kyr. The N. Atlantic SST rise as early as 17.7 cal. kyr or before ranging from Portugal northward is prior to the Heinrich (H1) cooling [*Lagerklint and Wright*, 1999]. The subsequent cooling and freshening [*Bard et al.*, 2000] linked to iceberg discharge into the N. Atlantic is further supported by an inferred absence of conventional deep meridional overturning circulation

(MOC) between 17.5 –15 cal. kyr (Figure 3) [*McManus et al.*, 2004].

[13] The ^{14}C kyr AMS chronology of deglaciation for the southern Laurentide margin we present agrees with the evidence of minimal sea level rise of 10–20 m at Barbados by 17.5 cal. kyr [*Yokoyama et al.*, 2000; *Peltier and Fairbanks*, 2006]. This retreat, along with the early European deglaciation, must have led to freshening of the N. Atlantic, increased winter sea ice, and reduced AMOC, which may have sustained an ice sheet in northeastern North America. The consistency of our results across numerous sites spanning 22, 000 square kilometers and the absence of any results older than 16 cal. kyr indicate that the landscape was either totally ice-covered or extremely cold and sedimentologically unstable. The onset of widespread lake formation in the stabilized landscape beginning 16 cal. kyr with rapid warming led the way to swift colonization of plants from adjacent unglaciated regions to the west (PA) and south (NJ), and lake organic sedimentation throughout by 14.7 cal. kyr. We propose that a strong water vapor feedback from abundant lakes and emerging warmed landscapes would have contributed to the Bølling warming as increased AMOC also resumed despite the continuing meltwater to the N. Atlantic. Accelerated by positive terrestrial and atmospheric feedbacks, a rapid rise in global sea level culminated in Meltwater Pulse 1A.

3.6. Defining Deglaciation and Implications of the AMS ^{14}C/^{10}Be Dating Conundrum

[14] We envision that boreal insolation and CO_2 -induced warming initiated the thinning southeastern portion of the Laurentide melt in place, but the resulting cold meltwater-laden N. Atlantic with reduced AMOC beginning at 17 cal. kyr delayed the latitudinal northward retreat. In contrast, the Midwestern portion of the Laurentide had begun its significant retreat from 23–16 cal. kyr [*Curry et al.*, 2010] in a more continental climate with warmer summers. Midwestern ice-walled lakes demonstrate melting ice and instability throughout this time. The delay of southeastern ice sheet pull-back presented here is interpreted from the apparent lack of any record of deposition in numerous small lakes while varves in large river valleys were emplaced, responding to small amounts of summer melt on a primarily ice-covered landscape. Minimal sea level rise and the benthic marine oxygen isotope curves showing little shift prior to 17.5 cal. kyr is consistent with this late ice-melt scenario as is the timing of Gulf of Mexico warming SST at 18 cal kyr followed by 16 – 14.7 cal. kyr cooling [*Williams et al.*, 2010] as well as the subsequent initiation of lake organic sedimentation regionally at 14.7 cal kyr (Table S1). Conversely, high Arctic conditions must have prevailed for at least 5 millennia with landscape instability to prevent permanent lakes from forming if ice indeed had pulled back from the margin, but we consider this possibility very unlikely because of the ability of vegetation to rapidly colonize unconsolidated glacial deposits [*Fastie*, 1995].

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References

Balco, G., and J. M. Schaefer (2006), Cosmogenic-nuclide and varve chronologies for the deglaciation of southern New England, *Quat. Geochronol.*, *1*, 15–28, doi:10.1016/j.quageo.2006.06.014.

Balco, G., J. Briner, R. C. Finkel, J. A. Rayburn, J. C. Ridge, and J. M. Schaefer (2009), Regional beryllium-10 production rate calibration for late-glacial northeastern North America, *Quat. Geochronol.*, *4*, 93–107, doi:10.1016/j.quageo.2008.09.001.

Bard, E. F., F. Rostek, J. Turon, and S. Gendreau (2000), Hydrological impact of Heinrich events in the subtropical northeast Atlantic, *Science*, *289*, 1321–1324, doi:10.1126/science.289.5483.1321.

Berger, A. L. (1978), Long-term variations of daily insolation and Quaternary climatic changes, *J. Atmos. Sci.*, *35*, 2362–2367, doi:10.1175/1520-0469(1978)035<2362:LTVODI>2.0.CO;2.

Broecker, W., D. Peteet, and D. Rind (1985), Does the ocean-atmosphere system have more than one stable mode of operation?, *Nature*, *315*, 21–26, doi:10.1038/315021a0.

Clark, D. H., P. R. Bierman, and P. Larsen (1995), Improving in situ cosmogenic chronometers, *Quat. Res.*, *44*, 367–377, doi:10.1006/qres.1995.1081.

Connally, G. G., and L. Sirkin (1986), Woodfordian ice margins, recessional events, and pollen stratigraphy of the mid-Hudson Valley, in *The Wisconsinan Stage of the First Geological District, Eastern New York*, edited by D. H. Cadwell, *N. Y. State Mus. Bull.*, *455*, 50–72.

Cotter, J. F. P., E. B. Evenson, L. A. Sirkin, and R. Stuckenrath (1986), The interpretation of "bog-bottom" radiocarbon dates in glacial chronologies, in *Correlation of Quaternary Chronologies*, edited by W. C. Mahaney, pp. 299–316, Geo Books, Norwich, U. K.

Curry, B., M. Konen, T. Larson, C. Yansa, K. Hackley, H. Alexanderson, and T. Lowell (2010), The DeKalb mounds of northeastern Illinois as archives of deglacial history and postglacial environments, *Quat. Res.*, *74*, 82–90, doi:10.1016/j.yqres.2010.04.009.

Dyke, A. S., A. Moore, and L. Robertson (2003), Deglaciation of North America, scale 1:7000000, *Geol. Surv. Can. Open File*, *1574*.

Fastie, C. (1995), Causes and ecosystem consequences of multiple pathways of primary succession at Glacier Bay, Alaska, *Ecology*, *76*, 1899–1916, doi:10.2307/1940722.

Fickert, T., D. Friend, F. Grunninger, B. Molnia, and M. Richter (2007), Did debris-covered glaciers serve as Pleistocene refugia for plants? A new hypothesis derived from observations of recent plant growth on glacier surfaces, *Arct. Antarct. Alp. Res.*, *39*(2), 245–257, doi:10.1657/1523-0430(2007)39[245:DDGSAP]2.0.CO;2.

Francus, P., R. Bradley, T. Lewis, M. Abbott, M. Retelle, and J. Stoner (2008), Limnological and sedimentary processes at Sawtooth Lake, Canadian High Arctic, and their influence on varve formation, *J. Paleolimnol.*, *40*, 963–985, doi:10.1007/s10933-008-9210-x.

Grimm, E. C., L. Maher, and D. Nelson (2009), The magnitude of error in conventional bulk-sediment radiocarbon dates from central North America, *Quat. Res.*, *72*, 301–308, doi:10.1016/j.yqres.2009.05.006.

Karrow, P. F., B. G. Warner, and P. Fritz (1986), Reply to J. F. P. Cotter, E. B. Evenson, L. Sirkin, and R. Stuckenrath, *Quat. Res.*, *25*, 259–262, doi:10.1016/0033-5894(86)90063-3.

Keigwin, L. D., G. Jones, and S. Lehman (1991), Deglacial meltwater discharge, North Atlantic deep circulation, and abrupt climate change, *J. Geophys. Res.*, *96*, 16,811–16,826, doi:10.1029/91JC01624.

Kneller, M., and D. Peteet (1993), Late Quaternary climate in the ridge and valley of Virginia, USA: Changes in vegetation and depositional environment, *Quat. Sci. Rev.*, *27*, 2467–2472.

Lagerklint, I. M., and J. D. Wright (1999), Late glacial warming prior to Heinrich event 1: The influence of ice rafting and large ice sheets on the timing of initial warming, *Geology*, *27*, 1099–1102, doi:10.1130/0091-7613(1999)027<1099:LGWPTH>2.3.CO;2.

Lambeck, K., and J. Chappell (2001), Sea level changes through the last glacial cycle, *Science*, *292*, 679–686, doi:10.1126/science.1059549.

Maenza-Gmelch, T. (1997), Late-glacial – early Holocene vegetation, climate, and fire at Sutherland Pond, Hudson Highlands, southeastern New York, USA, *Can. J. Bot.*, *75*, 431–439, doi:10.1139/b97-045.

McManus, J. F., R. Francois, J. Gherardi, L. D. Keigwin, and S. Brown-Leger (2004), Collapse and rapid resumption of Atlantic meridional

circulation linked to deglacial climate changes, *Nature*, *428*, 834–837, doi:10.1038/nature02494.
McWeeney, L. (1994), Archeological settlement patterns and vegetation dynamics in southern New England in the Late Quaternary, PhD thesis, 258 pp., Dep. of Anthropol., Yale Univ., New Haven, Conn.
Peltier, W. R., and R. G. Fairbanks (2006), Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record, *Quat. Sci. Rev.*, *25*, 3322–3337, doi:10.1016/j.quascirev.2006.04.010.
Peros, M. C., and K. Gayewski (2009), Pollen-based reconstructions of late Holocene climate from the central and western Canadian Arctic, *J. Paleolimnol.*, *41*, 161–175, doi:10.1007/s10933-008-9256-9.
Reimer, P., et al. (2009), IntCal09 and Marine09 radiocarbon age calibration curves, 0– 50,000 years cal BP, *Radiocarbon*, *51*, 1111–1150.
Ridge, J. C. (2004), The Quaternary glaciation of western New England with correlations to surrounding areas, in *Quaternary Glaciations-Extent and Chronology Part II*, edited by J. Ehlers and P. L. Gibbard, pp. 169–199, Elsevier, Amsterdam, doi:10.1016/S1571-0866(04)80196-9.
Stone, B., and H. W. J. Borns (1986), Pleistocene glacial and interglacial stratigraphy of New England, Long Island, and adjacent Georges Bank and Gulf of Maine, *Quat. Sci. Rev.*, *5*, 39–52.
Stone, B. D., S. D. Stanford, and R. W. Witte (2002), Surficial geologic map of northern New Jersey, *U.S. Geol. Surv. Misc. Invest. Ser. Map*, *I-2540-C*.
Stuiver, M., and P. Grootes (2000), GISP2 oxygen isotope ratios, *Quat. Res.*, *53*, 277–284, doi:10.1006/qres.2000.2127.
Walker, M. J. C. (1995), Climatic changes in Europe during the last glacial/interglacial transition, *Quat. Int.*, *28*, 63–76, doi:10.1016/1040-6182(95)00030-M.
Watts, W. A. (1979), Late Quaternary vegetation of central Appalachia and the New Jersey coastal plain, *Ecol. Monogr.*, *49*, 427–469, doi:10.2307/1942471.
Willard, D. A., C. Berhardt, G. R. Brooks, T. M. Cronin, T. Edgar, and R. Larson (2007), Deglacial climate variability in central Florida, USA, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *251*, 366–382, doi:10.1016/j.palaeo.2007.04.016.
Williams, C., B. P. Flower, D. W. Hastings, T. P. Guilderson, K. A. Quinn, and E. A. Goddard (2010), Deglacial abrupt climate change in the Atlantic Warm Pool: A Gulf of Mexico perspective, *Paleoceanography*, *25*, PA4221, doi:10.1029/2010PA001928.
Yokoyama, Y., K. Lambeck, P. DeDekkar, P. Johnston, and L. K. Fifeld (2000), Timing of Last Glacial Maximum from observed sea level minima, *Nature*, *406*, 713–716, doi:10.1038/35021035.